BARD Final Report US-4885-16

Improving sustainability of greenhouse production using semi-transparent flexible photovoltaic films

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Three year research project

Abstract

Alternative energy-integrated controlled environment agriculture, such as agrivoltaics for greenhouses, can offer sustainable crop production practices. Organic photovoltaic technology (OPV) offers a unique opportunity which can help tune to absorb light not required for crop growth for power generation and to transmit a spectrum that is beneficial for the crop, and with large scale roll to roll manufacturing capabilities. The project objectives were to: **1)** determine the effect of OPV application on greenhouse interior climate, crop yield and responses, **2)** estimate the potential of electricity production by OPV as affected by season and installation pattern, **3)** evaluate light quality under the OPV panels, **4)** establish guidelines for the application of flexible OPV sheets as cover materials or shading elements of greenhouses.

Major conclusions, solutions, achievements: **1.** The radiometric, thermal and electrical characteristics of commercial OPV module were evaluated with experimental prototype unit and with greenhouse deployments. **2.** Modeling based study estimated that about 49% coverage was sufficient to meet the energy demand of the off-grid greenhouse (134 m^2 ground area) based on the environmental control systems and lettuce crop modeled in the study. Various roof OPV coverage ratios were evaluated. The growing season can be extended with acceptable crop yield with OPV-integrated greenhouse during the summer period. **3.** The average value of radiation transmittance in the PAR region of the tested OPV modules were 22–26%. The fill factor of OPV modules changed during the day and was in the range of 0.24 – 0.38 as single modules and 0.20-0.40 as large rolls deployed on greenhouse. **4.** Variations on power conversion efficiencies (PCE) were observed among single sheet modules and large rolls deployed on greenhouse within average PCEs of 0.8-1.8%. **5.** 23% shading by OPV resulted in a lower canopy temperature with tomato crop and a lower nonhomogeneous radiation in the greenhouse. Shading by the OPV modules, in the hot summer season, improved the growth of tomato plants, yield, and quality in comparison to an unshaded greenhouse. The light use efficiency (ration of produce yield to cumulated light received by the crop) with tomato crops under OPV were significantly higher. **6.** The fresh shoot weigh of lettuce with Butterhead *Rex*, Romaine *Breen* were 50-55% higher and with *Bughati*-Red Oak Leaf with 31% higher under control greenhouse compared to those grown under OPV coverage. However, measured crop yields and crop quality under control and OPV coverage were both within desired marketable yield and quality. More leaf pigmentation with colored varieties were observed with lettuce grown without OPV cover. **7.** OPV can be used for shading and electricity generation however, it is expensive and degrades rapidly. Strategic OPV deployment alternatives for greenhouses should be evaluated to reduce OPV degradation and improving energy conversion efficiency and electricity production. **8.** OPV devices installed inside the greenhouse showed slower degradation and therefore longer lifetimes, compared to OPVs installed on top of the greenhouse. Although output of the panels outside the greenhouse were higher at installation, around 2 months after installation the panels inside the greenhouse yielded higher outputs compared to the panels outside. Integration strategies and methods of deploying OPVs inside the greenhouse should be investigated in further studies. **9.** Spatial variability due to the nonhomogeneous shading by OPVs was studied and compared with a greenhouse shaded by a conventional 25% black shading net. Spatial variability of microclimate and plant parameters was similar in the two greenhouses. Shading by OPV modules did not affect the energy partitioning in comparison to a shaded greenhouse. ***Implications, both scientific and agricultural:*** OPV appears suitable for greenhouse shading and electricity generation but is currently expensive. The currently available dimensions of OPV modules are too small to replace conventional greenhouse cover films. Additional studies are required to improve OPV efficiency and determine optimal placement either inside greenhouses or on the cover and the best shading percentage without resulting in significant reduction in crop yield and quality. Future studies should investigate whether the nonhomogeneous radiation distribution created by the OPV strips results in significant spatial variabilities such as physiological differences (e.g. transpiration and water consumption, photosynthesis) between crops in the shaded and unshaded areas. It is also of interest to determine the effect on the crop, of combining OPV modules with polyethylene covers with different haze properties. To reduce the nonhomogeneous shading on one hand and increase the electricity generation, on the other hand, it is advisable to aim for full coverage of the roof by OPV modules. For that, production of OPV modules with high transmittance in the spectral ranges where photosynthesis efficiency is high is recommended.

Summary Sheet

Publication Summary

PubType	IS only	Joint	US only
Other	0	0	2
Reviewed	0	5	0
Thesis - MSc.	0	0	1

Training Summary

Trainee Type	Last Name	First Name	Institution	Country
M.Sc. Student	Okada	Kensaku	The University of Arizona	USA
Ph.D. Student	Waller	Rebekah	The University of Aizona	USA
Ph.D. Student	Friman	Maayan	Volcani Research Center	Israel

Contribution of the collaboration:

Cooperation between the research groups was based on mutual design and implementation of the experiments such that adequate and complementary data was collected in both countries. The expertise of the three teams had a synergetic effect. The Israeli team, under Dr. Teiltel's leadership, of the Agricultural Research Organization (ARO) in Volcani Center has 25 years experiences in microclimate and plant parameter measurements. The team of the Triangle Research and Development Center (TRDC), under Dr. Yahia's leadership, has over 25 years of experience in both theoretical and practical aspects of photovoltaic technology. Dr. Kacira of UA-CEAC team has more than 20 years of experience with greenhouse and plant energy balance, autonomous plant health and growth monitoring, photovoltaics integrated greenhouse systems, automation and control in greenhouses. At the beginning of the project, the project teams had several Skype calls to discuss measurement techniques and strategies to incorporate the OPV elements in the greenhouses. Regular e-mail correspondence as well as periodic Zoom meetings were held to communicate about project progress, data analysis, manuscripts development and submissions. All investigators were involved in discussing the data obtained, its analysis and interpretations. Drs. Kacira and Teitel had an opportunity to meet in person during their participation and project related presentations both at the GreenSys 2017 International Symposium in Beijing-China and GreenSys 2019 International Symposium in Anger-France to discuss about project progress, activities. This meeting along with discussions with other project team members enabled a Phase 2 proposal and submission to BARD which is currently under review. On June 16th, 2020, the BARD team along with the Director of Plant Protection Services and Acting Chief Scientist at the Israeli Ministry of Agriculture were hosted by or co-PI Dr. Ibrahim Yehia, the Scientific Director of TRDC and Dr. Esther Magadley. On behalf of our project team, they were provided detailed information about the progress and outcomes of our BARD project being conducted on OPV integrated greenhouse system. The very positive feedbacks and encouragements our project team received was an additional important driving force to the development and Phase II BARD research proposal submission. Due to the Covid-19 pandemic the travels of PI of the Israeli team to USA and PI of the US team to Israel was canceled. The results of the study were jointly presented in few conferences and published in peer reviewed journal articles.

Achievements

Significance of main scientific achievements or innovations

Based on our knowledge, this project is the first study with large area OPV application and with both experimental and modeling-based research. It evaluated performance of OPVs for electrical and thermal performances, crop responses with yield and quality and the resulting environmental condition under OPV covered greenhouse. The outcomes of this project documented valuable information effects of outdoor irradiance and environmental factors on the performance of OPV. It highlighted limitations based on film degradation and opportunities to improve energy conversion efficiency. Furthermore, to provide a complete view it examined crop yield and quality and showed enhancement opportunities. The results of the study emphasize the need to better match the spectral properties of OPVs to the action spectrum of greenhouse-grown plants. The results of this project provide valuable insights for manufacturers of the OPV technology to improve and offer suitable products for agrivoltaics applications with greenhouse and shade houses.

The study clearly showed that it is feasible to grow tomatoes in a greenhouse with 25% shading by OPV modules during the hot summer season of a Mediterranean climate and obtain a good yield with good quality comparable to yield and quality from a conventional greenhouse. In semi-arid Arizona conditions, with 100% OPV roll deployment (with photoactive area of 75.8% per OPV sheet) on greenhouse roof with tomato crop, the crop yield was only 10% higher in control compared to those under OPV cover while the crops received 30-40% less average weekly daily light integrals under OPV. Thus, the light use efficiency (ratio of produce yield to accumulated light above crop canopy) of the crops under OPV were higher. This also indicated that high OPV coverage would not significantly reduce the produce yield enabling greater energy production with increased OPV coverage especially during warmer times of the year. During the cooler months, Dec-Feb, a dynamic control strategy with OPV deployment can achieve higher yields with maximum energy production capabilities which should be further evaluated.

With OPV roll deployment (photoactive area of 75.8% per OPV sheet) on greenhouse roof with lettuce crop, measured crop yields and crop quality under both control and OPV coverage were both within the desired marketable yield quality for the varieties evaluated, with OPV coverage not causing limitations on the marketable yield and quality. This result showed that the OPV with large coverage on greenhouse roof can produce marketable lettuce with potentials to achieve highest possible energy generation capabilities.

Furthermore, the study showed that despite the nonhomogeneous shading of the OPV strips, there were no consistent differences between the OPV covered and control greenhouses in terms of the spatial variability of air temperature, relative humidity, number and mass of fruits, canopy height, or leaf temperature. Further, the nonhomogeneous shading by OPVs virtually did not affect the energy partitioning in comparison to homogeneous shading by nets. It was shown that the mean daily power conversion efficiency (PCE) η with single OPV sheets and large rolls deployments was equal to about 0.8-1.8%, much lower than with commercial silicon modules (15 – 20% lab-based measurements). The recent lab based PCEs with OPVs are higher, around 15-17%, however their PCEs especially with large size OPVs are much smaller under outdoor settings as observed in the current project. Thus, there is still much to improve in the commercial-size modules to reach the higher 15-17% OPV efficiency recently reported for laboratory scale modules. Nevertheless, even with the current low efficiency (1-2%) and small ratio of roof area covered by OPVs (25-35%) it is possible to cover most of the electric power required by a greenhouse during summer in a Mediterranean and semi-arid climate.

Based on the results of the current project, we have also identified unique opportunities for alternative OPV deployment and operations which can improve longevity of the deployed OPVs in a greenhouse system and enhance electric energy generation with much improved power conversion efficiencies. For instance, an alternative OPV mounting and deployment procedure that can reduce the stresses on the panels and connections in addition to protecting the panels from extreme weather conditions is needed. This can reduce the degradation of the panels, increase their lifetimes and lead to higher outputs throughout the lifetime of the panels. We found that placing the panels inside the greenhouse and mounting them in affixed position unaffected by movement, reduced the degradation rate of the OPVs by protecting them from outdoor environmental stresses, leading to longer lifetimes of the panels. Although the lower incident irradiance on the panels inside the greenhouse reduces their output, the OPVs do have high efficiencies in diffuse light conditions and could therefore operate relatively well in these conditions, which deserve further investigation. This deployment alternative along with a dynamic deployment strategy, e.g. deploying and stowing, based on the outdoor environmental conditions, crop growth stage and requirements, deserves further investigation.

Agricultural and/or economic impacts of the research findings

Based on our results, the Israeli Ministry of Agriculture issued new regulations regarding the installation of photovoltaic panels in greenhouses. Up to now the ministry recommended to avoid installation of PV panels. Since few months ago, they recommend installation with a maximum coverage of about 20% of roof area. This will contribute to the increase in use of renewable energy in Israel on one hand and provide money savings or relatively stable additional income (when connected to the electric grid) on the other hand. The project outcomes provides valuable information and insights for OPV manufactures to further improve designs and manufacturing of OPVs suited for integration to greenhouse systems which can lead to enhanced electrical energy production and enabling to create environments for improved crop yield and quality with potential resource savings with positive economic and environmental impacts.

Publications for Project US-4885-16

Status	Type	Authors	Title	Journal	Vol:pg Year	Coun
Published	Reviewed	*M. Friman Peretz, F. Geoola, M. Teitel, I. Yehia. A. Levi, S. Ozer, L. Rosenfeld, A. Levy, E. Magadley, R. Brikman*	Examining the Spectral and Thermal Properties and Electricity Production Efficiency of Organic Photovoltaic Modules with regard to possible Application as Greenhouse Cover.	***ActaHorticulturae***	1268 : 233-240 2020	Joint
Published	Reviewed	*Magadley, E., I. Yehia, M. Teitel, M. Friman Peretz, M. Kacira.*	Outdoor behavior of organic photovoltaics on a greenhouse roof.	***Sustainable Energy Technologies and Assessments***	37 : Article 100641. 2020	Joint
Published	Other	*Kensaku Okada, Murat Kacira*	Crop production and Energy Generation in Organic Photovoltaics Integrated Greenhouse	***Oral presentation at University of Arizona Controlled Environment Agriculture Center Annual Summer Research Retreat, August 11th, Tucson, Arizona.***	: 2017	US only
Published	Thesis - MSc.	*Kensaku Okada*	Modeling and Optimization of Crop Production and Energy Generation for Economic Profit in an Organic Photovoltaics Integrated Greenhouse		: 2018	US only
Published	Other	*Kensaku Okada*	Modeling and Optimization of Crop production and Energy Generation for Economic Profit in Organic Photovoltaics Integrated Greenhouse	***UA-CEAC Summer Research Retreat Presentation***	: 2018	US only
Published	Reviewed	*Friman-Peretz, M., F. Geoola, S. Ozer, E. Magadley, I. Yehia, A. Levi, R. Brikman, S. Gantz, A. Levy, M. Kacira, M. Teitel*	Microclimate and crop performance in a tunnel greenhouse shaded by organic photovoltaic modules – comparison with conventional shaded and unshaded tunnels.	***Biosystems Engineering***	197 : 12-31 2020	Joint
Published	Reviewed	*Friman Peretz, M., F. Geoola, I. Yehia, S. Ozer, A. Levi, E. Magadley, R. Brikman, L. Rosenfeld, A. Levy, M. Kacira, M. Teitel*	Testing organic photovoltaic modules for application as greenhouse cover or shading element.	***Biosystems Engineering***	184 : 24-36 2019	Joint
Published	Reviewed	*Okada, K., Yehia, I., Teitel, M. and Kacira, M*	Crop production and energy generation in a greenhouse integrated with semi-transparent organic photovoltaic film	***ActaHorticulturae***	1227 : 231-239 2018	Joint

Appendix: Unpublished Data and Publications (submitted/in review and in preparation)

Waller, R., M. Kacira, E. Magadley, M. Teitel, I. Yehia, 2020. Evaluating performance of flexible, semi-transparent, large-area organic photovoltaic arrays deployed on a greenhouse. Solar Energy Journal (Submitted, under review)

The electrical performance of large scale, flexible, semi-transparent organic photovoltaic (OPV) arrays deployed on a curved greenhouse roof surface was evaluated. In a Python programming environment, a greenhouse roof model was developed which simulates a curved greenhouse roof with eight OPV rolls installed. Using an open-source solar modeling program, we calculated the incident solar irradiance on the entire curved surface of the OPV rolls and relate this to measured electrical data for the OPV rolls. In doing so, we were able to characterize the outdoor performance of the OPV devices in different irradiance conditions. The results from four months of electrical monitoring of the OPV rolls deployed on the study greenhouse are presented. This method is the first of its kind to characterize the electrical performance of commercially available, large-area OPV arrays deployed on a curved surface and can be expanded to other curved surface structures as well as other flexible PV technologies.

Waller, R., M. Kacira, T. Mahato, M. Teitel, I. Yehia, E. Magadley. 2021. Effects of greenhouse roof integrated semi-transparent large-area organic photovoltaic arrays on crop growth and yield. (In preparation)

This paper presents information on effects of greenhouse roof integrated semi-transparent large-area organic photovoltaic arrays on growth and yield of tomato and lettuce crop. In semi-arid Arizona conditions, with 100% OPV roll deployment (with photoactive area of 75.8% per OPV sheet) on greenhouse roof with tomato crop, the crop yield was only 10% higher in control compared to those under OPV cover while the crops received 30-40% less average weekly daily light integrals under OPV. Thus, the light use efficiency (ratio of produce yield to accumulated light above crop canopy) of the crops under OPV were higher. This also indicated that high OPV coverage would not significantly reduce the produce yield enabling greater energy production with increased OPV coverage especially during warmer times of the year. During the cooler months, Dec-Feb, a dynamic control strategy with OPV deployment can achieve higher yields with maximum energy production capabilities which should be further evaluated. With OPV roll deployment (photoactive area of 75.8% per OPV sheet) on greenhouse roof with lettuce crop, measured crop yields and crop quality under both control and OPV coverage were both within the desired marketable yield quality for the varieties evaluated, with OPV coverage not causing limitations on the marketable yield and quality. This result showed that the OPV with large coverage on greenhouse roof can produce marketable lettuce with potentials to achieve highest possible energy generation capabilities.

Magadley, E., Teitel, M., Friman-Peretz, M., Ozer, S., Levi, A., Yasuor, H., Kacira, M., Waller, R., Yehia, I., 2021. Integrating organic photovoltaics (OPVs) into greenhouses: Performance of OPVs and their effect on greenhouse microclimate and crop. Sustainable Energy Technologies and Assessments. (Submitted, under review)

This paper presents the electrical performance of organic photovoltaic modules (OPVs) on top of a polyethylene covered greenhouse high tunnel and reports on the micro-climate and crop performance inside the OPV covered tunnel, in a Mediterranean climate. Although the output was highest under direct irradiance, OPV module efficiencies on the tunnel roof peaked when they were not in direct incident irradiance. The installation of the modules across the arch of the tunnel roof from east to west led to a more distributed output throughout the day, an advantage both for onsite use and for grid connection. Modules installed on the tunnel roof had an accelerated degradation compared to modules installed on a flat frame next to the tunnel. Covering 37% of the tunnel roof by the OPVs, resulted in a 25% lower spatially averaged global solar radiation, lower canopy temperature, higher leaf area index, higher cumulative yield, than in an adjacent control tunnel covered by a polyethylene film only. When the control tunnel was covered by a shading net, resulting in a similar spatially averaged shading percentage in the two tunnels, the spatially averaged microclimate and crop performance in the two tunnels were very similar.

Maayan Friman-Peretz, Shay Ozer, Asher Levi, Esther Magadley, Ibrahim Yehia, Farhad Geoola, Shelly Gantz, Roman Brikman, Avi Levy, Murat Kacira, Meir Teitel. 2020. Energy partitioning and spatial variability of air temperature, VPD and radiation in a greenhouse tunnel shaded by semi-transparent organic PV modules. (Submitted, under review)

A study related to the application of organic photovoltaic (OPV) modules in greenhouses is presented. The study considers the impact of nonhomogeneous shading by semi-transparent OPV modules, placed on the cover of a greenhouse tunnel housing a tomato crop, on energy partitioning and the spatial variability of radiation, air temperature and vapour pressure deficit (VPD) within the tunnel. Experiments were conducted in two similar tunnels that were covered by a diffuse polyethylene sheet. Flexible semi-transparent strips of OPV modules were placed on 37% of the roof area of one tunnel, creating an approximately 23% nonhomogeneous shading, while the other tunnel served as a control greenhouse, which was homogeneously shaded by a 25% black shading net. The results show that on cloudy days with high diffuse radiation, spatial variability of radiation in the OPV tunnel was smaller than on sunny days with low diffuse radiation. Conversely, variability in air temperature and VPD did not change much with the change in diffuse radiation. Except when diffuse radiation was high, no significant difference in the energy partitioning between nonhomogeneous shading by OPVs and homogeneous shading by a conventional shading net was observed. Most of the net radiation in the tunnels was converted into latent heat. With a high solar elevation angle, the spatial variability of radiation within the tunnel was higher than with a low solar elevation angle. Additional experiments are needed to determine the best arrangement of semitransparent OPV modules on the roof, without resulting in any significant increase in spatial variability.

Magadley, E., Yehia, I., Teitel, M., Friman-Peretz, M., Waller, R., Kacira, M. 2021. Comparison of organic photovoltaics installed inside and outside a greenhouse and the effect on output and lifetime. (In preparation)

This paper presents a comparison of organic photovoltaic modules installed on top and inside a greenhouse. At installation, the modules outside the greenhouse, which were exposed to higher irradiance levels than the modules inside the greenhouse, had higher outputs. However only two months after installation, the modules inside showed higher outputs compared to the modules outside the greenhouse. This was due to their slower degradation due to not being exposed to harsh outdoor weather conditions.

Other relevant material

Conference presentations and other products

Okada, K., Yehia, I., Teitel, M. and Kacira, M. Crop production and energy generation in a greenhouse integrated with semi-transparent organic photovoltaic film. Greensys 2017 - International Symposium on New Technologies for Environment Control, Energy-Saving and Crop Production in Greenhouse and Plant Factory, August 20-24, Beijing, China.

M. Friman Peretz, F. Geoola, M. Teitel, I. Yehia. A. Levi, S. Ozer, L. Rosenfeld, A. Levy, E. Magadley, R. Brikman 2020. Examining the Spectral and Thermal Properties and Electricity Production Efficiency of Organic Photovoltaic Modules with regard to possible Application as Greenhouse Cover. XI International

Symposium on Protected Cultivation in Mild Winter Climates & I International Symposium on Nettings and Screens in Horticulture. Tenerife (Spain – Canary Islands, January 27-31, 2019.

Teitel, M. Photovoltaics in agriculture. Intelligent Agriculture and Use of Drones, Ministry of agriculture, Hadera, Israel, 2.3.2019.

Teitel, M. Experiments with OPV. Machinery and Technology for Smart and Innovative Agriculture, Rishon Lezzyon, 30.5.2019

Maayan Friman Peretz, Farhad Geoola, Ibrahim Yehia, Shay Ozer, Asher Levi, Esther Magadley, Roman Brikman, Lavi Rosenfeld, Shely Gantz, Avi Levy, Murat Kacira, Meir Teitel. Effect of organic photovoltaic modules on top of a greenhouse tunnel on its microclimate. 22nd Sede Boqer Symposium on Solar Electricity Production, September 24-25, 2019 (won best poster 3rd place).

Magadley, E., Teitel, M., Friman-Peretz, M., Kacira, M., Yehia, I. Greenhouse Integrated Organic Photovoltaics. 22nd Sede Boqer Symposium on Solar Electricity Production, September 24-25, 2019. (poster)

Maayan Friman Peretz, Farhad Geoola, Ibrahim Yehia, Shay Ozer, Asher Levi, Esther Magadley, Shely Gantz, Meir Teitel. Potential use of organic photovoltaic (OPV) modules in greenhouse cultivation. EU PVSEC 2020, 37th EU PVSEC, 07 - 11 September 2020, online event.

Magadley, E., Yehia, I., Friman-Peretz, M., Geoola, F., Ozer, S., Levi, A., Gantz, S., Teitel, M. Organic Photovoltaic (OPV) Greenhouse, ZIM AgriPhotonics Conference, 08 September 2020, online event.Meir Teitel, Maayan Friman-Peretz, Shay Ozer. 2020. Agrivoltaics in protected cultivation. IsraelAgri, Israeli Agriculture International Portal. http://israelagri.com/greenhousetech2020/index.html#p=4

Magadley, E., Yehia, I., Dakka, M. Greenhouse integrated organic photovoltaics for food and energy security. The Second International Computerized Conference: Applied Research and Science Teaching. 09 December 2020, online event.